

Final Report for the Multi-Autonomous Ground-robotic International Challenge (MAGIC) 2010

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Analytical Software Inc.

ABSTRACT

This final report describes multiple Unmanned Ground Vehicles (UGVs) and their autonomous navigation techniques developed by the US-Asian Team that can safely expedite reconnaissance in cluttered urban environments. The developed multi-UGV system consists of four high-performance UGVs with efficient and intelligent autonomous navigation capabilities. They can detect, locate, classify, recognize and track suspicious Objects of Interest (OOI) and then neutralize any confirmed threats while mapping the entire indoor and outdoor environments. As a result of the development and implementation of the hybrid feature-based/scan-matching Simultaneous Localization and Mapping (SLAM) technique, the multi-UGV system can localize OOI and build a map within the targeted accuracy of 25 cm. The (1) implementation of the model-predictive control and the hybrid SLAM and (2) the Occupancy Grid Mapping (OGM) on the Graphic Processing Unit (GPU) after formulating them within a single recursive Bayesian estimation framework, this enables autonomous navigation at speeds of at least 8 km/h. Performance tests in two buildings and one outdoor area have shown the efficacy of the developed multi-UGV system.

ORIGINAL PLAN

A - Introduction

i. Statement of the Problem – The basic goal is to show how groups of autonomous UGVs can work as a unit searching urban areas with minimal intervention by the operators. Today when ground robots are used they are often slow and tedious since these UGVs are often manipulated manually, thereby increasing the cost and time of searching dangerous areas. The objective is to reduce the operators' workload so they can easily and dynamically manage multiple unmanned vehicle systems (UVS). This technology will accelerate the development of autonomous UVS in areas such as: task allocation, multi-UVS control, tactical behavior, machine intelligence, dynamic planning and re-planning, data and sensor fusion, human machine interfaces and multi-aspect situational awareness. It will also improve the current human-to-vehicle control ratios by demonstrating that multi-UVS cooperatives can operate effectively with limited supervision by humans in realistic urban environments.

ii. Conceptual Solution Proposed – The US-Asian Team led by Analytical Software Inc. will design these robots to be both cost-effective and meet the demanding technological requirements to win (SLAM for mapping, and communication and control systems to insure the UGVs act as a team to track and neutralize OOI). These robots will be equipped with lasers, GPS, compasses, and other sensors to avoid obstacles and cameras which will use vision-based technology to automatically identify whether a person or object is a threat or an innocent bystander. While there are many ground robots available today, their major weakness is their degree of autonomy and cost. Robots, which are equipped with these capabilities, cost \$25,000 or more per unit and the US-Asian Team will demonstrate that through the innovative use of network communications, such as 802.11s mesh networks, and technologies such as SLAM, the unit prices of these autonomous robots could be only several thousand dollars each.

Then the networked UGVs will share high-quality video and mapping data, including information about innocent bystanders, thereby permitting safe reconnaissance and tracking in urban environments.

iii. Graphic Overview of Overall Systems Architecture – The Control Station and the UGVs will be linked through a wireless mesh network. Mapping data collected from this network will be fused with simulated UAV imagery into an actionable database. The original UAV imagery will provide an initial grid accurate to 50 cm, which the SLAM technology will continuously update and enhance. Then software at both the Control Station and on the UGVs will automatically devise the best strategy to locate and disable all hostile OOI. There are two categories of robots: (1) Sensor UGVs, which map the area and can neutralize mobile OOI and (2) Disruptor UGVs, which can neutralize static OOI. Figure 1 (on the next page) shows that the UGVs found a suspicious backpack. If it matched the Electro/Optical (EO) threat profile, then it will be automatically disabled by the Disruptor UGV. This unified network permits the robots to rapidly complete their mission.

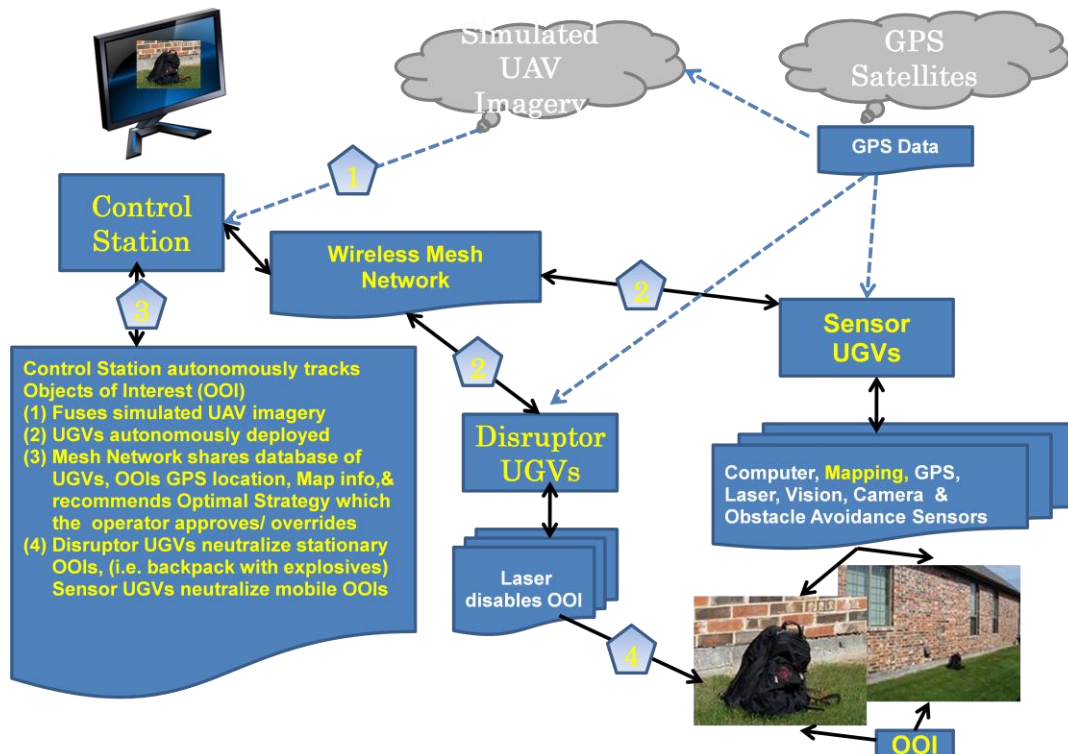


Figure 1- Graphic Overview of Overall Systems Architecture

iv. Work breakdown and milestones – The key factors to succeed at this mission are to have: (1) dependable, inexpensive robots with cameras, lasers and other sensors which permit vision-based tracking of OOI and obstacle avoidance, (2) SLAM technology to permit real-time update of maps which are generated as the robots travel up to 10 km/hr (roughly 2.8 meters/sec) and (3) a robust communications network which links the UGVs and a Control Station with updated data, videos and maps of the challenge area. This report shows that up to 8 laser-equipped, SLAM-capable UGVs, costing roughly \$4,000 each, will expedite mapping and tracking of OOI. Since robots can be lost due to breakdowns or even snipers, 8 units will insure that network communications are maintained and the mission can succeed. Then a series of courses, each up to 300 by 200 meters, can be covered within the 3 ½ hour time limit. The goal is to maintain continuous situational awareness of any suspicious objects so that these autonomous robots can neutralize these threats. The milestones to develop the UGVs during this 12 month project are shown in Figure 2 (on the next page).

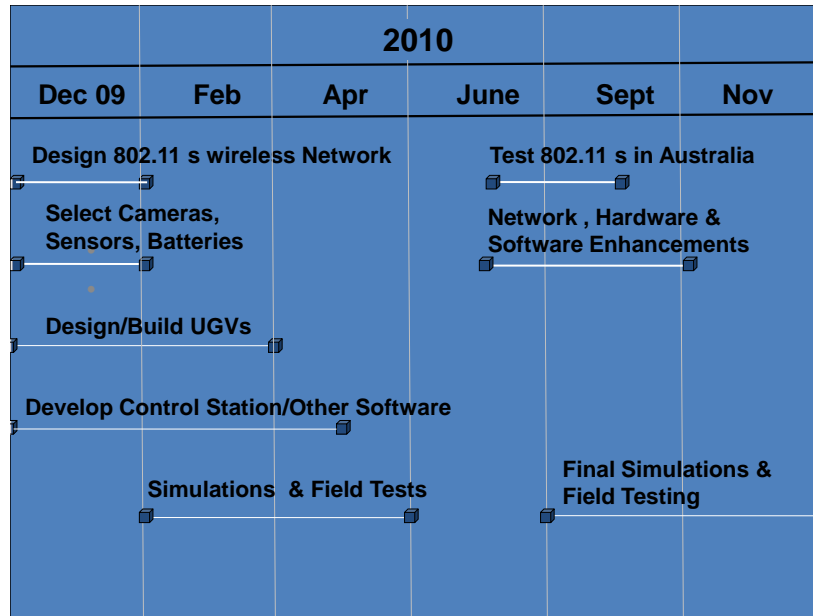


Figure 2- Key Milestones

The following summarizes the most important challenges required to succeed:

Key network/video issues- In designing the network, the objective will be to seamlessly share UGV video and data from any location in an area of up to 500 by 500 meters (size of the total course which is divided into smaller sections for each of 3 phases). To insure continuous sharing of actionable information for both the robots and the Control Station, all UGVs will be equipped with a wireless mesh node. These self-healing networks are crucial for this competition since they can automatically reroute traffic if a node fails. In addition, the network will also conform to 802.11n which offers up to 300 Mbps capacity, 5 times the capacity of previous Wi-Fi technologies, such as 802.11a/g. Simulations and field tests will determine which mesh technology is the most cost-effective and provides the best coverage. Since maintaining communications is crucial, a backup system (Table 1) might be considered such as (1) ZigBee Mesh, which has low power requirements and long range, or (2) even programmable Smartphones (such as the iPhone 3G, Blackberry etc.). Tests have shown that UGVs can be remotely controlled using only mobile phones.

		Range (Meters) ⁽²⁾		Data Rates ⁽²⁾
Communications	Unit cost ⁽²⁾	Indoors	Outdoors	Mbps
Primary Network				
Mesh Network Node	\$420-4,000	up to 50	Up to 500	Up to 300
Backup Network				
Zigbee (802.15) ⁽¹⁾	\$80	up to 100	up to 1,000	0.25
Cellular 3G	\$150	Varies	Varies	>1 (HSDPA)

Table 1 – Tradeoffs for Communications Options

(1) ZigBee or similar technology (2) Range, price, data rates vary widely based on antenna, power etc and these high mesh node distances are obtained using a 7 dBi Omni directional antenna and a Hi Powered 802.11n radio.

Note the Cellular range varies based on factors such as the distance to the nearest Cell Tower.

Key design requirements of robots – Given the budget constraints, and the challenges in MAGIC 2010, it's clear that customized laser-equipped, SLAM-capable, networked UGVs will be crucial for success. The goal will be to keep the UGVs as light and inexpensive as possible and yet make them completely autonomous with their onboard computers, sensors and batteries.

Tactical Issues– There will be 8 Robots which will be grouped into two squads of 4 units each. Each squad will include: (1) two fully-equipped Sensor UGVs which can map and disable mobile OOI (2) one Disrupter UGV which will neutralized static OOI (this unit will be less expensive since it will not map) and (3) one very low-cost \$1,700 backup Sensor UGV per squad. This backup unit will be minimally equipped. Since two sensor robots are needed to neutralize mobile OOI, this insures that each squad can continue its mission even with losses. Obviously, more robots increase the chances of success. However, too many robots on the field will add both costs and complexity, so the goal will be to use only up to 8 robots.

C. Ground Vehicle Component & Systems - Some of the most widely used commercial off-the-shelf (COTS) UGVs are either too expensive or not capable of meeting the mission guidelines. For example, two widely used ground robots (Figure 3 on page 5) are: (1) iRobot's PackBot which can provide reconnaissance and disable mines and improvised explosive devices (IED) and (2) MobileRobot's Pioneer 3-AT (P3-AT) which is used for research and by government and other customers. Thousands of these robots have been sold to the military, police departments and universities around the world. Both UGVs have many capabilities however the Packbot is not primarily designed for mapping and a fully-equipped unit can cost over \$100,000 while a P3-AT with SLAM can cost up to \$25,000. During MAGIC 2010, the US-Asian Team will use an existing P3-AT which it will upgrade with a Light Detection and Ranging (LIDAR) sensor for SLAM. However, the P3-ATs are expensive and it will not be cost effective for this competition to use more COTS P3-ATs since four of these units could cost \$100,000.



Figure 3 – iRobot's Packbot (on the left) and MobileRobots' P3-AT (on the right)

The budget to prepare for the competition is only \$100,000 and up to 70 percent will be needed for personnel for hardware/software development, simulations and testing.

Therefore the hardware budget for UGVs will only be about \$30,000. And as noted before, assuming up to 8 robots will be needed to maintain communications during 3 ½ hours while mapping and tracking OOI, then the unit cost of each UGV could only be roughly \$4,000 each. The following sections show how the US-Asian Team can create these customized low-cost robots by using an innovative combination of SLAM technology, low-cost lasers and networked UGVs. A manufacturer which mass produces battery-powered units bid to produce these customized UGVs for only \$900 per UGV. These units can travel up to 10km/hr and run continuously for 4 hours. The US-Asian Team will upgrade this basic unit into a fully autonomous UGV with onboard computers, sensors and mesh network communications.

Key UGV Design targets (The MAGIC requirements are in Bold)

Wt/Size – Less than 40 kg, and less than 2 meters high and ideally less than 0.5 meters wide and long to fit in 0.9 meter passageways. Then it can turn in a circle in a doorway. A lighter UGV reduces battery requirements. Also, climbing 10 cm is useful.

Speed – Up to 10 km/hr - The robots must turn and move forwards/backwards at up to 10km/hr. Of course a faster UGV helps meet time constraints.

Computer, Mapping and Tracking – The UGV's SLAM data will be combined with GPS outdoor imagery provided by a simulated UAV to generate a map of the MAGIC course. And the onboard computer will have sufficient storage and processing capabilities so that it can continue mapping even if communications are lost.

Power - It will be a major advantage if the UGVs have sufficient power to last for 3 ½ hours during the competition. Preliminary estimates are that a 21 Amp-Hour battery should be sufficient. However, as field tests progress, alternative power sources and battery sizes will be considered.

The US-Asian Team has extensive experience developing autonomous ground and air robots with vision-based tracking systems and obstacle avoidance and components of the US-Asian Team's UGVs are shown in Table 2 on the next page.

Table 2 – Cost of the Primary New UGVs (*)

<u>Component</u>	<u>Company - Model</u>	<u>~Cost \$</u>
UGV up to 10km /hr, runs 4hrs on batteries	Mass produced model-customized	900
Mesh network gear & backup communications	Cisco & lower-cost sources	500
PTZ Camera	Panasonic , others	300
Embedded PC 1.6 GHz, 1GB RAM, 160GB HD	Many sources	400
GPS, Digital Compass	Garmen, Honeywell, etc	200
2 Axis Tilt Sensor and other sensors	Many sources	120
Lasers to assist in SLAM & obstacle avoidance	URG-04LX-UG01	1,175
Obstacle Avoidance & other Sensors	Many sources such as SICK	90
Battery (at least 21 Amp-Hour)	Many sources such as PowerSonic	150
Subtotal for Average UGV		<u>\$3,835</u>
<u>Accessories for some UGVs</u>		
Simple mechanism to deploy mesh nodes	Customized - 4 units	150
Periscope-device to look around corners	Customized - 4 units	100
Laser Range Finder (30 m range)	Hokuyo UTM-30LX/N - 1 unit	5,500

*The US-Asian Team will use an existing P3-AT, and it will build 7 new UGVs: (1) 5 new UGVs will cost up to \$4,000 per UGV plus \$5,500 for a Hokuyo laser and (2) 2 less expensive \$1,700 backup UGVs. Quotes were from multiple vendors. These prices are the most cost-effective.

To handle these challenges in previous competitions, innovative yet expensive solutions were utilized. For example, in the DARPA Challenge the MIT team used a Land Rover equipped with 10 Blades each with two 2.33 GHz dual-core processors, 12 SICK LIDARs, 15 radars and 5 cameras. However, in MAGIC 2010, with a hardware budget of about \$30,000 for robots, this mandates a more cost-effective use of technologies. Therefore in addition to an existing P3-AT, the **US-Asian Team will build 7 new UGVs: (1) five UGVs (shown above), (2) two very basic low-cost \$1,700 backup UGVs and finally (3) four \$500 deployable mesh nodes (for a total cost of roughly \$30,000).** One of the UGVs in Table 2 will be upgraded with a new Hokuyo UTM-30LX/N which scans rapidly at 25ms/scan and has a good range of up to 30 meters. Since the US-Asian Team's existing P3-AT is already equipped with similar technology, these two units will quickly map the course. Four sensor UGVs will also carry a \$500 deployable mesh node which will be strategically placed around the course to enhance communications. Finally, the two \$1,700 robots will serve one mission, these backup units will be directed by the squad to track and neutralize mobile OOI. They will only be equipped with limited computer and communications capabilities. The net result is these 2 squads totaling eight networked robots will be optimized for both outdoor and indoor mapping and tracking.

D. UGV autonomy & coordination strategy (by task) -The networked UGVs will continuously share operational information to form a unified actionable database.

UGV autonomy – Each UGV can operate independently with GPS and sensors for obstacle avoidance, mapping and tracking. However, the wireless mesh network links them so they continue to act as a team. And with lasers, each UGV knows its location relative to each other so the unified map can guide the squad as a unit to their targets.

Obstacle avoidance – Lasers and Ultrasonic sensors will be used to avoid obstacles.

Indoor/Outdoor Navigation – There are limitations to GPS and the US-Asian Team will use SLAM data fused with UAV GPS imagery data to both create the maps and precisely navigate through the course.

Coordination Strategy (by Task) - The following strategies will be used for each task:

(1) Explore and Map the Challenge Area and Track the Status of Cleared Buildings–The US-Asian Team’s SLAM technology does not require GPS and it maps both indoors and outdoors with an accuracy of 3 cm without GPS. By combining GPS data from the simulated UAV imagery with the SLAM data, this expedites mapping. With a few fixed GPS reference points throughout the course, this corrects any SLAM errors (3 cm) while maintaining roughly the 50 cm GPS accuracy provided by the UAV. And this automatically keeps track of the status of the mapping in each Phase.

(2) Automatic/optimal route planning for the UGVs – With a unified actionable map/database, and by using optimization techniques to cover the challenge area in the least time, the ideal route to complete the mission can be planned.

(3) OOI Detection, Recognition, Identification – All of these goals can be achieved because of three of the US-Asian Team’s technologies: (1) its vision-based systems which permit target detection and tracking (2) a unified map database created with SLAM which precisely identifies locations and (3) a robust primary and backup mesh network which links the robots at all times. These technologies will easily permit the following:

- o **Autonomous target hand-over between Sensor & Disruptor UGVs**

- o **Automatic target detection, classification and recognition**

- o **Collaborative target tracking and target cross-cueing**

The Sensor UGVs will locate and identify the OOI and track them autonomously using the US-Asian Team’s vision-based technology. If the EO profile of the OOI matches the threats then the OOI will be neutralized.

(4) Neutralize OOI - The networked UGVs will act as a team: (1) if a Mobile OOI is encountered, the two closest Sensor UGVs will automatically be sent to neutralize it (2) however if it is a static OOI, the closest Disruptor UGV will be deployed.

E. Sensors, processing & mapping for UGVs-

Sensors – Each of the primary Sensor UGVs will be equipped with a wide variety of sensors including lasers for mapping and location and obstacle avoidance, plus GPS and digital compasses and Pan/Tilt/Zoom (PTZ) cameras for OOI identification and tracking (as shown in Table 2)

Computers – The onboard UGV computer will be sufficient to continue mapping and tracking OOI even if the primary communication links were lost. The following embedded computer is available for \$400 - Intel Atom Z530 1.6GHz, 1 GB RAM, 160 GB hard disk: 6 USB slots (More expensive models will be used if field tests determine the SLAM or tracking software require more capabilities).

Mapping - Distributed Particle SLAM 2.0 - This mapping software was originally developed by Dr. Austin Eliazar as part of his doctoral dissertation at Duke University. It produces maps in real time with only a single pass through of the targeted area with only a few landmarks and without any offline corrections. DP-SLAM uses a Kalman

particle filter with an occupancy grid to plot objects on a map. It uses distributed particle mapping (DP-Mapping) which significantly eliminates redundancies of tracking objects. This research creates maps with an accuracy of 3 cm in an area of up to 500 by 300 meters where the data is collected from a laser while the robot is moving at 40 cm/sec.

Enhanced DP SLAM – “3-D GPS SLAM Simulator” - Dr. Eliazar will advise the US-Asian Team on how to enhance DP SLAM 2.0 making it both more efficient and powerful. The objective will be to have ground robots autonomously: (1) collect data for DP SLAM while the UGVs are moving up to 10 km/hr (2.8 m/sec) (2) combine this data with the simulated UAV imagery which includes GPS and (3) compensate for errors caused by vibrations during the higher speeds. The goal will be to map an area of up to 300 by 300 meters within an hour. In 2004, DARPA funded millions of dollars for the Centibots project led by SRI International and Stanford University where 100 robots mapped indoors. In the MAGIC project, the objective will be to demonstrate that today a group of up to 8 inexpensive robots can map indoors and outdoors. By fusing SLAM data with the UAV imagery, this will maintain the 50 cm accuracy of the GPS data by correcting any cumulative SLAM errors with GPS reference points. Also, this will expedite outdoor mapping since these precise GPS reference points will help plan the optimal way to survey the course even before the UGV left the starting point.

DP SLAM has mapped large areas such as a massive 120 x 60 m convention center, even while people walked in the hall (left side, Figure 4). The MAGIC simulated UAV GPS imagery will be fused with data from DP SLAM to create an integrated GeoTIFF map of the course (both indoors and outdoors). This map will be accurate to 50 cm and this data will be logged at a rate of 1 Hz. In addition, **these GeoTIFF maps and SLAM and other UGV data will automatically create a “3-D GPS SLAM Simulator”** (right side, Figure 4). **This is not just an interactive GPS map; it is also a simulator which models the robot’s physical properties including its motors and gears.**



Figure 4 – 120 x 60m Conference Center mapped using DP SLAM (left). A “3-D GPS SLAM Simulator” (right)

F. Operations in GPS-denied Environments – As noted previously, with DP SLAM and lasers, the UGVs can operate in GPS-denied environments so they can continue mapping and searching without GPS, both indoors and outdoors. And the UGVs’ lasers plus other sensors such as ultrasonic sensors will provide obstacle avoidance. Also, the UGVs will be equipped with digital compasses which will help maintain their bearings. Finally, the communications networks (primary and backup) will provide oversight by the Control Station. In short, while the UGV’s onboard GPS is

helpful, it is primarily DP SLAM in conjunction with the fused data of the simulated UAV imagery which provides data for maps for navigation.

Limitations of GPS/DGPS/RTK – The accuracy of GPS or Differential GPS (DGPS) signals varies widely due to factors such as the number of satellites available.

Statistically this variation is called the Distance Root Mean Square (DRMS) which is the “radius of a circle containing 98 percent of the GPS readings”. The Committee (PNT), which sets GPS standards, noted that reliable GPS sensors have a DRMS 6 meters in diameter ⁽¹⁾. Real Time Kinematic (RTK), with accuracies of a few centimeters, is ideal for surveying; however, it’s expensive. And in urban areas, GPS is hampered by the lack of a clear line of sight (LOS) to both the satellites and the ground base stations.

G. Processing and fusion of provided Metadata (from UAV) - Data imagery will be provided by an Unmanned Aerial Vehicle (UAV) in real time in WGS84 coordinates at an update rate of approximately 1Hz. This data will be fused with the information collected by the UGVs to map the area. The UAV imagery provides key GPS reference points to correct any cumulative mapping errors from DP SLAM as the robots move far from the Control Station. The wireless network will continuously transmit UGV data back to the Control Station where the unified most up-to-date map will be plotted and shared. In addition, the latest information about OOI including non-combatants will be fused with the latest map data. Then the optimal strategy will be autonomously devised. The Control Station software will periodically ask the operator to approve the optimal deployment of UGVs and how to complete all phases of the mission on time.

H. Human-machine interface (HMI) - Figures 5, 6 and 7 show the type of information available to the Control Station operator including maps with GPS data which shows the location of all the UGVs, OOI, obstacles, etc. The Wireless Network will constantly update a central database of all key data including video feeds from the UGVs. And with a simple mouse click, all important key data will be graphically accessible.

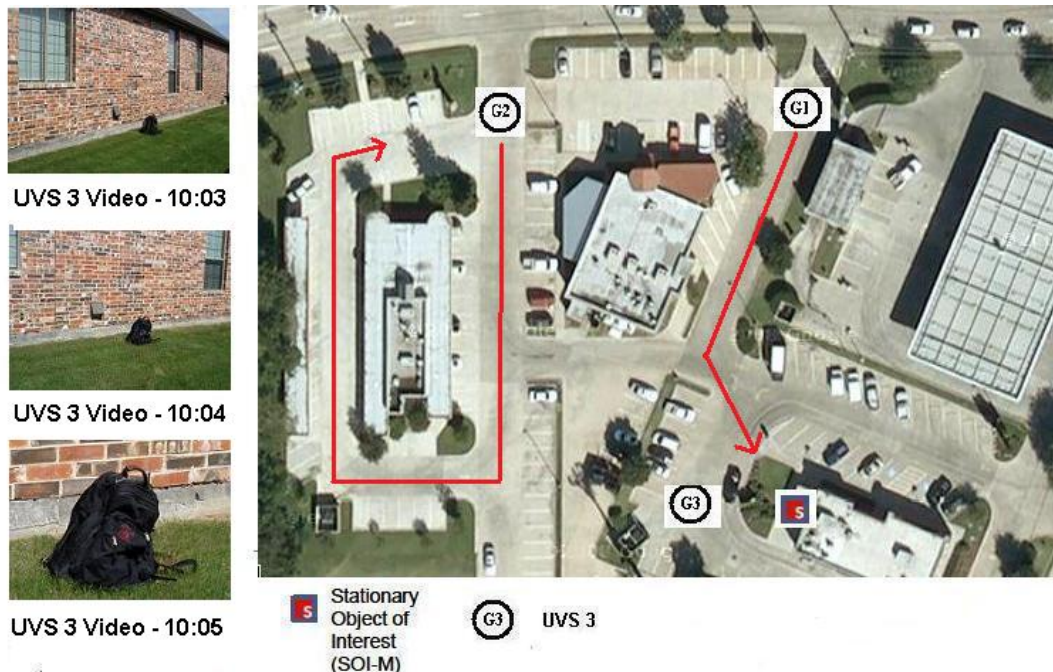


Figure 5- Sample of the Graphical Interactive Data available at the Control Station

I. Operational approach/missions operations strategy - The key goal is to have ground robots act as an autonomous integrated team while the Control Station operators can immediately make strategic overrides to insure a successful mission. To do this it is crucial to (1) maintain network communications at all times and (2) have sufficient number of robots to achieve this mission. By limiting the cost of each robot to \$4,000, this insures that up to 8 robots are available for mapping, maintaining network communications and tracking OOI. If multiple UGVs are lost due to sniper fire or other factors then these squads might have to regroup to form a new team.

Maintaining Network connections is the key to a successful mission – With a primary and backup network, all mapping data and other data will be continuously up-to-date throughout the network. Then, the Control Station software can automatically maintain the optimal deployment of the UGVs across all parts of the Challenge area both indoors and outdoors. To sustain network efficiencies, when possible, the UGVs will maintain line of sight for each node back to the Control Station (Figure 6).

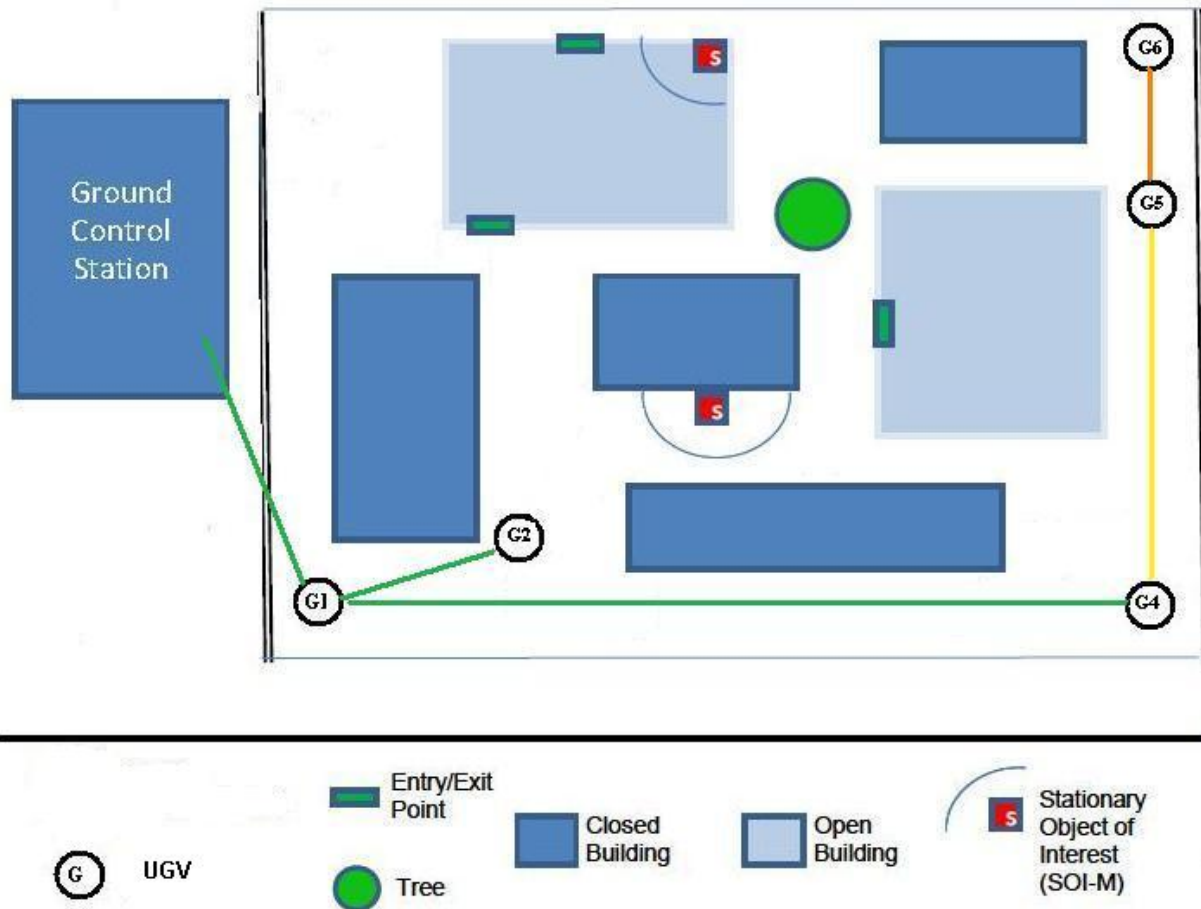


Figure 6- Graphical Network Status/Simulation Available at the Control Station

Figure 6 graphically illustrates the reduction in throughput of roughly 50 percent per hop in the network.

J. Risk reduction strategy -The following shows how each of the following electrical, physical other obstacles will be handled:

i. EMI / RFI & electrical - Radio Frequency Interference (RFI) - Legacy 802.11 networks such as 802.11g have been subject to RFI from devices such as cordless phones ,other 802.11 networks that fill the 2.4 GHz ISM band and even jammers. In general, techniques such as error-correcting and frequency-hopping can be used to reduce interference. And dual band 802.11n systems avoid much of this RFI by working on both the 2.4 GHz and 5 GHz frequencies. Also, if the primary network is jammed the backup mesh or cellular network can be used.

ii. Vibration & physical - Shocks will be added to the UGVs to minimize vibration of all components on the UGVs. In addition, to avoid camera shake, and at the same time to reduce the bandwidth requirement capacity of the network, the video speed may be reduced to only 1 frame each 2 or 3 seconds. These stable images will allow strategic decisions to be made by the operator and also autonomous tracking of OOI. However, as long as the throughput of the communications links is available and the UGVs are not traveling quickly over rugged terrain, high quality 30 frame/sec video will be available. Also to insure accurate data measurements for SLAM, an IMU (or a 2 axis tilt sensor) will determine the orientation of the robot and a servo will continue to point the laser

horizontally so the laser correctly measures the distances to the wall and does not point towards the ground or sky. Finally, if shaking is a problem, the robot will slow down or even stop to insure accurate data.

iii. Modeling & Simulation

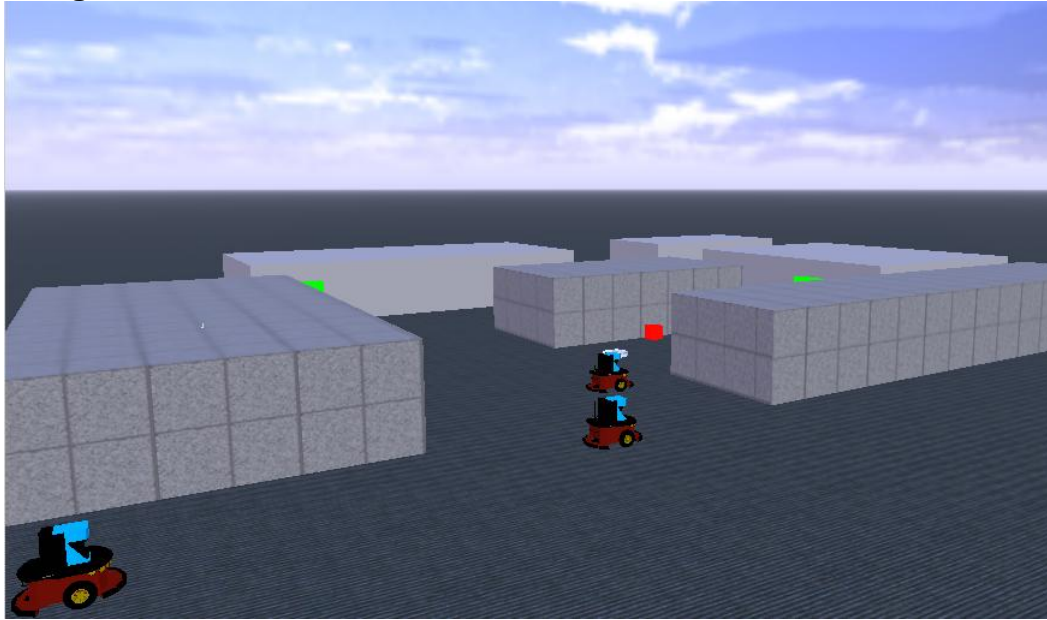


Figure 7- Simulation of the MAGIC Challenge area

The equipment and wireless networks will be modeled and tested under a number of scenarios using simulators such as **Microsoft Robotics Studio, MATLAB and the US-Asian Team's own simulations**. Figure 7 shows an interactive 3-D simulation of the MAGIC course which can be created in minutes using software developed for this competition. **In addition, by combining GPS data with SLAM data, this automatically turns the simulator into an interactive "3-D GPS SLAM Simulator"**. This model also permits the Control Station to simulate the network capacity and the optimal strategies for tracking and neutralizing OOI. The Network Capacity requirements will determine the type of communications equipment needed. The equipment and wireless networks will be modeled and tested under a number of scenarios. Then the optimal robot design will be finalized and the new UGVs will be built starting in the 2nd month of this project.

These simulations will confirm the key design requirements: the sensors needed to complete the mission, the optimal deployment of the mesh network, the electrical power required for the UGVs to operate continuously for 3 ½ hours and the resulting type of vehicle and its weight needed to meet all of these requirements. And the PTZ camera selection will insure that videos from the UGVs provide adequate detail for both Vision-based tracking and operator situational awareness of the Challenge area. The network capabilities will also define the UGV's computer requirements. Powerful network links can reduce the UGV's onboard processing power and battery requirements. The hardware and software systems will be designed to create a seamless, integrated network of autonomous, expendable robots which will succeed in their mission.

iv. Safety, E-Stop, Freeze & Lost-Link -In order to insure that the UGVs are within the course boundaries and also under the control of the judges in order to meet the Freeze and E-Stop requirements, the UGVs will only continue to operate while they maintain their communication links. If these links are lost, the vehicle will automatically stop until its communications are restored.

Safety, Speed Limits and Course Boundaries - The vehicle's ground speed will be monitored to insure the units do not exceed 10 km/hr. While, the rotation of the UGVs tires roughly estimates speed, these wheels can "spin" in loose gravel. The lasers, GPS and other onboard sensors, will more accurately monitor the speed of the vehicle. And the most accurate location data will be provided by DP SLAM where the onboard computers fuse the laser data with UAV GPS data thereby creating accurate maps which are shared across the mesh network. The onboard map and the shared maps accurately track each UGV's location and speed and keep them within the boundaries.

Finally, each UGV will have Laser or Ultrasonic sensors in order to avoid hitting mobile OOI, Noncombatants or obstacles such as buildings. Since units are penalized for collisions which are defined "as the main body of a UGV contacting an obstacle", each UGV will be equipped with "Feelers" such as pressure sensitive bumpers that detect contact with an obstacle. These are permitted (Section 12.1 of the MAGIC Guidelines) and will instruct the unit to freeze and slowly extract itself from the situation. Of course, the UGV speed will be reduced where there are many obstacles or in doorways in order to avoid collisions.

In order to neutralize static OOI the disrupter UGVs "must carry an eye-safe laser pointer for designating these objects". The laser selected will be eye-safe following the US Food and Drug Administration (FDA) guidelines. The FDA is responsible for safety standards for Lasers which are rated from Class I to Class IV (severe hazard).

E-Stop, Freeze - As noted in the MAGIC Guidelines each UGV must be equipped with: (1) a termination mechanism ("E-Stop") and (2) a "Freeze" (i.e. administrative stop) mechanism and the judges must be able to remotely trigger both of these options. "Freezing a vehicle means stopping the vehicle and immediately disabling any contribution that the vehicle can make to its own or the operators' overall situational awareness picture." In order to meet these requirements, the US-Asian Team will provide the Judges with an easy-to-use communications device which can disable or terminate any UGV. This information will link to the Control Station which will relay it to the appropriate UGV. However, if any UGV loses communications it will automatically be disabled in order to meet the MAGIC requirements.

Lost-Link (ZigBee or Cellular Backup Network) – If communications with the primary network is lost, then a backup network (previously shown in Table 1) will be used to control the UGVs. If the UGV's backup network also failed, then that UGV will automatically freeze and stop operations until communication links are reestablished.

v. Communications Architecture –A Technical and Regulatory Challenge

As noted previously, the key design objective of the communications network will be to continuously cover an area of up to 500 m x 500 m. The primary system will be a

wireless mesh network. Simulation studies will be conducted to confirm the performance of the mesh network and field tests in Japan, the US and Australia will be conducted prior to the competition.

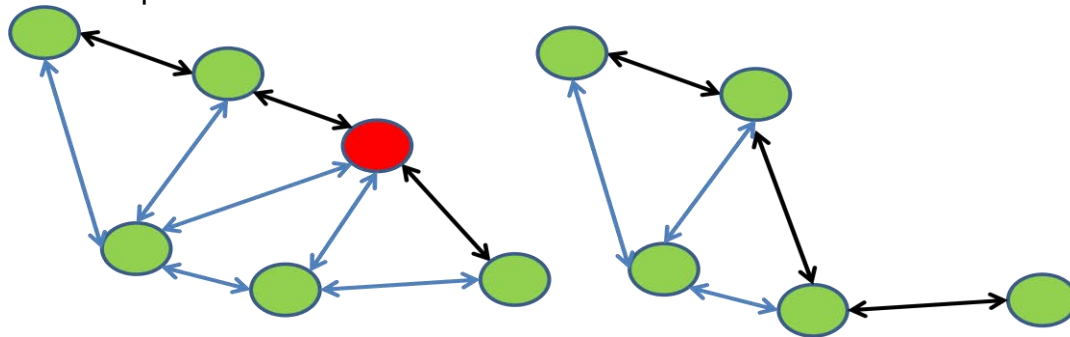


Figure 8- Self Healing Wireless Mesh Nodes (left before failure, right after failure)

The mesh networks the US-Asian Team uses are both self-configuring and self-healing, meaning that if one device fails (red node in Figure 8), the network will search for another device which is in range. In a typical Wi-Fi network the loss of a key access point can be crucial. But in a 802.11s mesh network, communications are automatically restored. The range for each node depends on its antenna and power. Obviously coverage can be improved by increasing the range of each node or adding additional nodes to extend the network signals. As noted before, the US-Asian Team will have four self-contained mesh nodes which can be deployed by the UGVs throughout the challenge area. Network simulations during the first two months of this project will identify the ideal antennas and power capabilities of each node to maximize coverage for the wireless network.

Regulatory constraints - Regulatory constraints limit which equipment is permitted. For example, Cisco, one of the world's leading suppliers for network communications, offers 3 different versions of same Access Point in Japan, Australia and the USA due to differing regulations in each country. Therefore to insure optimal performance of the equipment field tests in Australia will be performed prior to the competition in November 2010. And the final solution may be limited by both regulatory and technological constraints.

Backup Network - Since maintaining communications is crucial to the success of all phases of the competition, one of the following two backup networks will be considered. **ZigBee Mesh** – This is a very low-cost, easy to setup network. A ZigBee mesh network is “self healing” and if communications are lost between two nodes an alternative path is automatically sought. ZigBee is a wireless communications standard based on IEEE 802.15. The primary high-speed mesh network, which offers 802.11n speeds of up to 300 Mbps, tends to have shorter ranges than ZigBee. Of course, with more power and better antennas these ranges can be increased. However this increases the power requirements on the battery-powered UGV. On the other hand, some ZigBee devices have a range of up to 1,000 meters outdoors and up to 100 meters indoors and can operate for weeks on small batteries. Therefore if the primary mesh network loses

communications, the backup ZigBee network could automatically redeploy the UGVs so that the primary mesh communication links are reestablished.

Cellular - If the MAGIC rules permit Cellular networks, this backup option might be considered. Cellular networks are ubiquitous and Smartphones can be customized to collect and share data such as GPS, or video. However, data transfer is expensive. Also, indoors there may be limits to coverage and if the MAGIC competition were at an extremely remote location, mobile coverage might not even be available.

vi. Spectrum plan & usage – The MAGIC guidelines recommend using ‘Class License’ bands: 915-928 MHz, 2.4 GHz & 5.8 GHz. Both the primary mesh network and the ZigBee backup network operate in these frequencies. However some backup options which have better ranges utilize other bands. Initial discussion with the Australian Communications and Media Authority (ACMA), which regulates Australian radio communications and telecommunications, indicated a temporary scientific license can be obtained for these bands. So other frequencies might be considered including even a cellular backup option. The primary mesh nodes have an outdoor range of up to 500 meters or more since they use a good antenna, i.e. a 7 dBi Omni directional antenna, and a Hi Powered 802.11n radio. However, regulatory constraints may limit some options; therefore the most powerful mesh nodes permitted by ACMA will be tested in Australia prior to MAGIC 2010.

vii. Test Plan - These field tests will rigorously analyze all the capacities of the final systems: the control stations, the wireless network capabilities, the UGV mechanical capabilities as well as their ability to map and track and neutralize OOI, plus the ability of the UGVs to seamlessly work as an autonomous team as they accomplish their missions. The equipment and wireless networks will be tested under a number of scenarios continuously for 3 ½ hours. This will confirm that all aspects of the mission will succeed: (1) the UGVs perform the entire mission autonomously with only strategic guidance from the Control Station (2) DP SLAM creates maps at the required accuracy (50 cm), at sufficient speed to complete the course on time (3) the wireless mesh links are continuously maintained or if they are broken then the backup network assists in corrective measures to restore the primary mesh network (4) the UGVs can successfully identify, track and neutralize hostile OOI without hurting innocent civilians and (5) the onboard battery power is sufficient to last for 3 ½ hours (or at least minimal battery changes are needed). In order to insure that the UGVs operate without battery changes, alternative power supplies such as a generator may be considered. Since the primary and backup nodes together only cost \$500, the US-Asian Team’s inexpensive strategy to insure network coverage is to have the UGVs deploy mesh four nodes at strategic points on the course. This option would also be tested as would be the option for a rudimentary periscope-type device to allow the cameras to look around a corner.

The UGVs should be reliable since they are customized versions of mass-produced units. Also, preliminary test have shown that if the primary network fails, a backup cellular or mesh network permits the Control Station to continue monitoring and even controlling UGVs in the most remote sections of the course. For example, tests of the ZigBee mesh confirmed that it can maintain data communications and send small photos every 5

to 10 seconds even over 2 node hops. Tests have also confirmed that this ZigBee mesh and the primary mesh network can work without conflicts by using different radio channels. Additional tests have even shown that the navigation of a UGV and sending of videos can be accomplished using only programmable low-cost Smartphones. By June 2010, after testing the software and hardware, there will be a demo to the MAGIC's judges to confirm the status of the project. This will demonstrate that three autonomous UGVs (one P3-AT and two new low-cost UGVs) can map and track OOI under the strategic guidance of the operators at the Control Station. After a successful demo, then the remaining five UGVs will be built, tested and prepared for MAGIC 2010.

REFERENCES - (1) Oct 18, 2008, The National Executive Committee for Space-Based Positioning, Navigation, and Timing (PNT), set the DoD GPS accuracy for civilian signals to 4 meters RMS (7.8 meters, 95 percent). Their report says that with "Signal in Space (SIS) accuracy, well designed GPS receivers have been achieving horizontal accuracy of 3 meters or better (The radius is 3 meters and the diameter is 6 meters)."

FINAL ACCOMPLISHMENTS

The final accomplishments are different from the original plan. This is because of (1) the withdrawal of Chiba University due to the anti-American attacks by the Asahi Newspaper and (2) rejection by the MAGIC organizer to use the name the US-Asian Texas to participate in MAGIC2010. As a result, ASI teamed up with Dr. Furukawa's research group at Virginia Polytechnic Institute and State University to compensate for Chiba's withdrawal and also focused on developing fundamental technologies for multi-UGV systems rather than developing strategies to win MAGIC2010. Dr. Furukawa's group has one of the world's best reputations in the multi-UGV system research, and cooperation with them was the best choice to maintain the capabilities co-developed with Chiba.

A – Unmanned Ground Vehicles

i. Design – Figure 9 shows the final design of the multi-UGV system. The major components of each UGV are (1) sensors, (2) actuators, (3) E-stop, (4) processors, (5) a wireless module and (6) a battery. Sensors include (a) GPS and a compass for absolute localization, (b) a laser range finder and one pan/tilt camera for relative localization and mapping and (c) an Inertia Measurement Unit (IMU) in conjunction with encoders for dead-reckoning. The PicoStation wireless module is to relay data among all the UGVs and the base station through mesh network technology without complication. Most unique in the developed system is the use of a GPU in addition to the CPU and MCU. Image processing, localization and mapping, which are required for estimating mobile and static OOI, all observe node-by-node calculations. The nVidia GPU, together with CUDA library for general-purpose computing on graphics processing units (GPGPU) accelerates, not only image processing, but also localization and mapping such that real-time localization and mapping is possible.

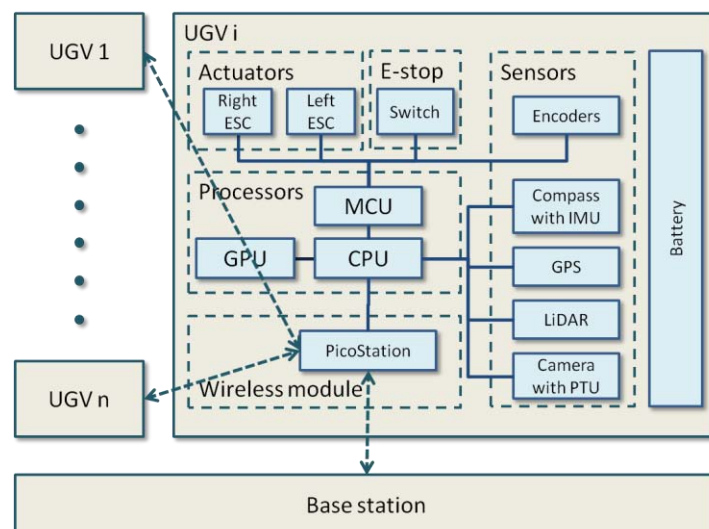


Figure 9 – Design of multi-UGV system

Due to the development of a new intelligent and sophisticated SLAM technique that is presented in the next subsection in addition to the aforementioned reasons, there were

changes in the design of the multi-UGV system. Table 3 lists the UGVs developed and their components. The major change is that four more expensive UGVs were built instead of seven new inexpensive UGVs. This is because the implementation of a LIDAR on each UGV according to the development of the intelligent SLAM technique since this setup, having a LIDAR with long-range high-accuracy measurement capability, allows accurate localization and mapping more efficiently. Three UGVs (UGVs 1-3), mounting Sick LIDAR, were built using Superdroidrobots Heavy Duty 4WD RC All Terrain Robot Kit, whereas one UGV (UGV 4), which mounts a light-weight Hokuyo LIDAR, was built using GEARS SMP Robot Kit.

In order to reduce the overall cost, the other components were those which satisfy technical requirements at the minimum cost. Razor IMU, Garmin GPS, Logitech Quickcam, Microcom PicoStation and Asus EeeBox are all those that were selected based on the criteria. Particularly noted is the Asus EeeBox. This is the smallest PC which has a nVidia GPU. The enclosure was chosen to enclose the EeeBox and the batteries.

Table 3 – Ground vehicle components

	UGV 1	UGV 2	UGV 3	UGV 4
Robot Kit	Superdroidrobots Heavy Duty 4WD	Superdroidrobots Heavy Duty 4WD	Superdroidrobots Heavy Duty 4WD	GEARS SMP
LIDAR	Sick LMS291	Sick LMS291	Sick LMS291	Hokuyo UTM-30LX
Compass with IMU	9Dof – Razor IMU	9Dof – Razor IMU	9Dof – Razor IMU	9Dof – Razor IMU
GPS	Garmin GPS 18x	Garmin GPS 18x	Garmin GPS 18x	Garmin GPS 18x
Camera with PTU	Logitech QuickCam Orbit AF	Logitech QuickCam Orbit AF	Logitech QuickCam Orbit AF	Logitech QuickCam Orbit AF
Wireless	Microcom PicoStation M2-HP	Microcom PicoStation M2-HP	Microcom PicoStation M2-HP	Microcom PicoStation M2-HP
On-board PC	Asus EeeBox (1.6GHz Intel Atom, nVidia ION)	Asus EeeBox (1.6GHz Intel Atom, nVidia ION)	Asus EeeBox (1.6GHz Intel Atom, nVidia ION)	Asus EeeBox (1.6GHz Intel Atom, nVidia ION)
Battery 1	24V LiPo battery (for motor)	24V LiPo battery (for motor)	24V LiPo battery (for motor)	12V NiMH battery (for motor)
Battery 2	12V LiPo battery (for EeeBox and PicoStation)	12V LiPo battery (for EeeBox and PicoStation)	12V LiPo battery (for EeeBox and PicoStation)	12V LiPo battery (for EeeBox and PicoStation)
Enclosure	Botego BO 62612L	Botego BO 62612L	Botego BO 62612L	Botego BO 62612L

ii. Development – Figure 10, on the next page, shows the developed four UGVs and Figure 11 shows the individual Superdroidrobots robot and the Gear robot. All the robots consist of a chassis, LIDAR, camera, wireless module and a computing unit. The development of the computing unit, which can be plugged and played on any set of drive train and sensors, has enabled the completion of four UGVs easily, and more UGVs can also be developed very easily.



Figure 10- The developed four UGVs



(a) Superdroidrobots Robot



(b) Gear robot

Figure 11- Individual UGVs

Table 4 summarizes the major specifications of the developed UGVs. UGVs 1-3 are heavier than UGV 4 due to the installation of 4.5 kg Sick LIDAR, but Sick LIDAR provides a longer range than Hokuyo LIDAR. The faster speed of UGVs 1-3 is a capability of Superdroid robot.

Table 4 – Specifications of the developed UGVs

	UGVs 1-3	UGV 4
Weight	9.5 kg	5 kg
Dimension	546 mm(l) x 571 mm(w) x 508 mm(h)	597 mm(l) x 538 mm(w) x 762 mm(h)
Maximum speed	15 km/h	6 km/h
LIDAR range	80 m	30 m
Camera resolution	640 x 480	640 x 480
Camera fps	30 fps	30 fps
Camera p/t angles	189 deg / 102 deg	189 deg / 102 deg

B – Navigation Techniques

i. Overview – Figure 12 shows the schematic diagram of the autonomous navigation implemented into the multi-UGV system. Localization of OOI, the vehicle itself and landmarks, which achieves SLAM, and occupancy grid mapping (OGM), which develop a map, are all carried out within a single recursive Bayesian estimation loop which consists of prediction and correction. The estimated locations of all are further used to determine the low-level control of the UGV to follow the desired path. While the SLAM, the OGM and the low-level control are performed at high frequency, the high-level control, which determines a series of waypoints that the low-level controller should follow, is executed less frequently.

The GCS in the current system collects all the results from the UGVs and visualizes the fused result. The GCS, at a frequency lower than those for the low-level and high-level controls, sends a request to all the UGVs and synchronously collects the results from the UGVs. The results are not combined but fused with a correct probabilistic fusing process so that those that multiple UGVs collected can be most appropriately utilized.

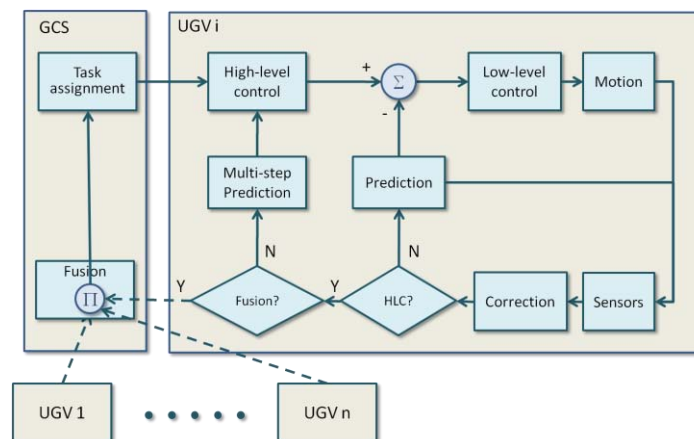


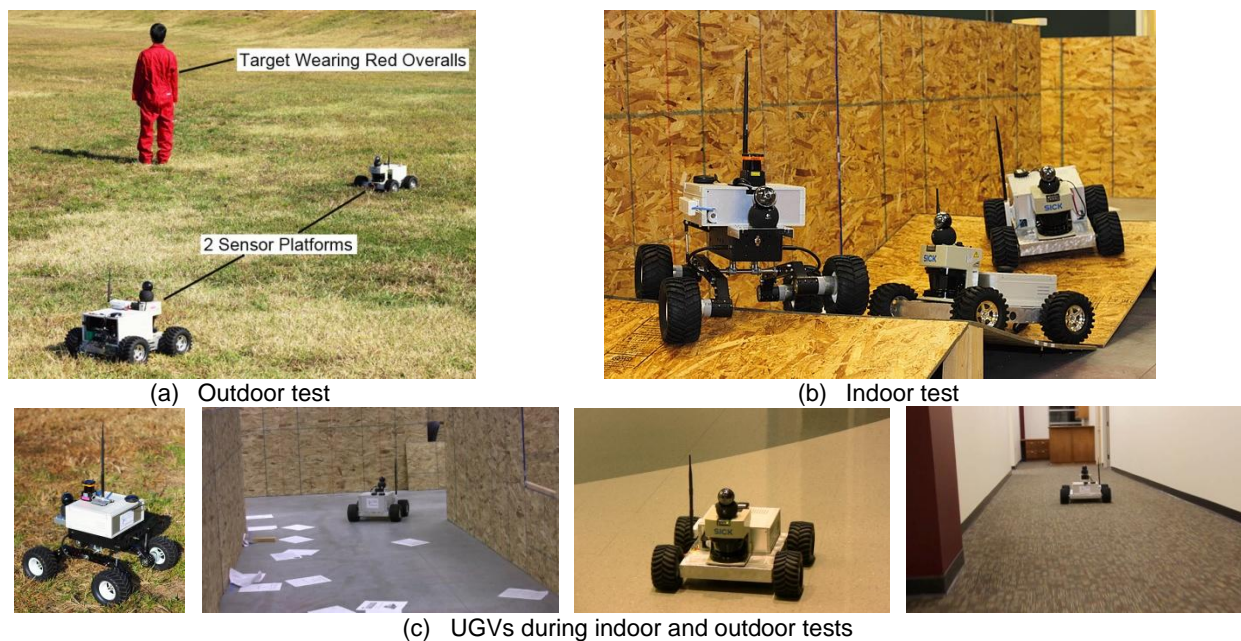
Figure 12- Autonomous navigation

ii. SLAM and OGM – The SLAM developed has an accuracy as much as 25cm for mapping and the localization has resulted in the combination of the feature-based SLAM and the scan-matching SLAM. While the feature-based SLAM treats landmarks as the analytical model, the scan-matching SLAM regards landmarks as templates of raw sensor data. As a result, one set of observations of landmarks gives data in multiple dimensions, and the hybrid method thus can perform SLAM more accurately. In indoor environments, the unavailability of the GPS makes the conventional SLAMs heavily dependent on the encoders and the compass and incorrect as the encoders accumulate errors while the compass data are often highly unreliable. The hybrid feature-based/scan-matching SLAM can localize and map without these sensors and achieve the accuracy of 25cm due to the use of multi-dimensional information. OGM is, similarly to SLAM, carried out by using LIDAR data. The OGM developed runs within the framework of recursive Bayesian estimation, so that the program execution is stable and reliable.

iii. Control – In order to control UGVs which operate at speeds of 6 km/h (speed of mobile OOI) or higher in real-time environments adopted for low-level control and high-level control are the LQG and the model-predictive control works most efficiently for the problem of concern. However, the adoption of the conventional techniques is not enough to achieve the desired speed since the control involves SLAM and OGM while the processing speed of the onboard computer is limited. Since many processes in localization and mapping are programmed within loops, it is possible to accelerate the speed of SLAM and OGM by implementing and running programs on a GPU. The SLAM and OGM programs were thus parallelized and able to be performed at a frequency of 3 Hz, which is fast enough to drive UGVs at speeds over 6 km/h.

C – Experimental Results

i. System in Operation – The UGVs were tested in both indoors and outdoors. Figure 13 shows snapshots of UGVs during the indoor and outdoor tests as well as the environments. Mobile and static objects of interest were placed in accordance to the instructions of MAGIC competition. Indoor environments also had obstacles specified in the MAGIC guidelines. Ground condition was also various as the pictures show.



(c) UGVs during indoor and outdoor tests
Figure 13 – Indoor and outdoor tests

Figure 14 (on the next page) shows the transition of the result of localization and mapping by two UGVs in the Graphical User Interface (GUI) developed. The second and the third figures show the intermediate result when the first and the second OOI have been detected whereas the fourth figure shows the final result. In the GUI, the top two figures show the global locations of the UGVs and OOI identified and the global map constructed. The bottom two figures, on the other hand, show the locations identified and maps constructed by each UGV. It is seen that the global map is constructed by fusing the maps of individual UGVs. The result also shows that the map is being

completed as time passes. This indicates the system is operating properly by making use of cooperative exploration by two UGVs.

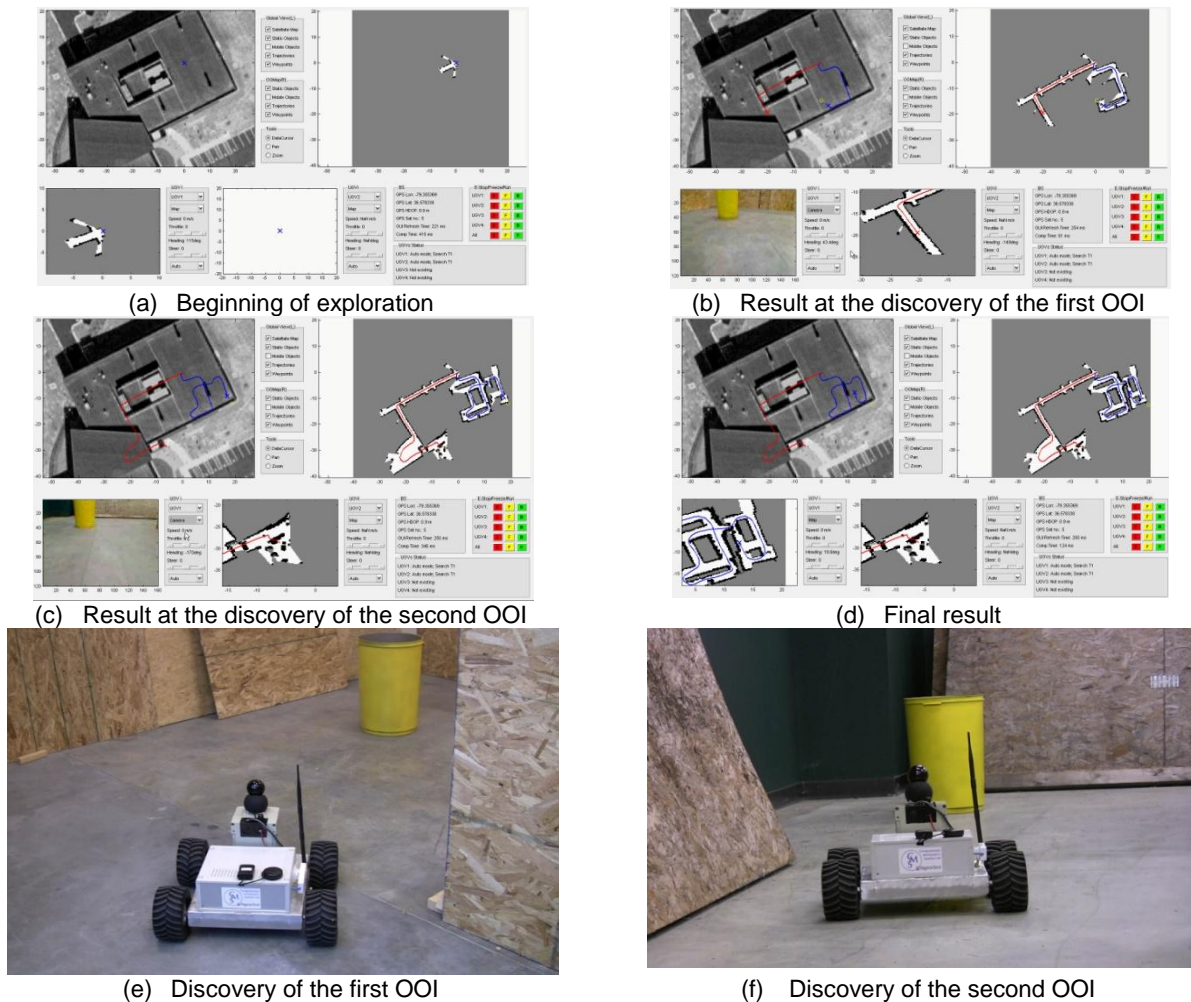


Figure 14 – System performance Test 1

Figure 15 (on the next page) shows a transitional result where the two UGVs started from different locations. The snapshots show another successful cooperative exploration and thus demonstrate the robustness of the developed multi-UGV system.

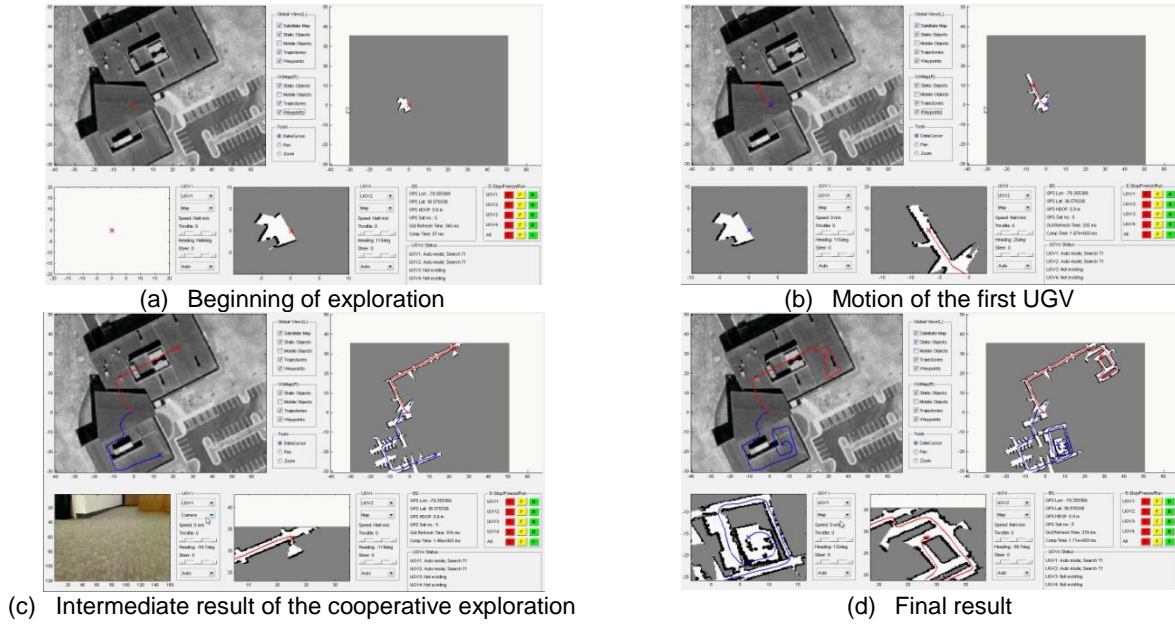
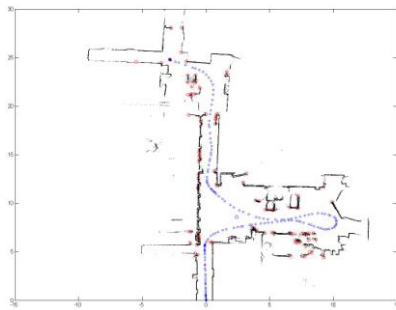
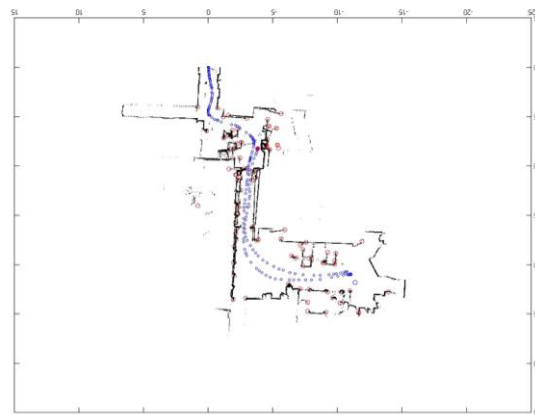


Figure 15 – System performance Test 2

The UGVs were tested to build a map and localize OOI in different environments. The tested environments include two buildings and one outdoor area. Figure 16 shows the two maps of one building (25 m x 30 m) created by a single UGV with the developed hybrid feature-based/scan-matching SLAM. Figure 16(a), on the next page, first shows a map when the UGV was driven from one end of the building to another end of the building. The map is well constructed with many walls aligned at right angles shown as they are. The maximum positional inaccuracy observed by the travel was 15 cm with an average of 6 cm, and the result indicates the effectiveness of the developed hybrid SLAM. Figure 16(b), on the next page, shows a map constructed when the UGV was driven from the upper end of the building and brought back to the start position after exploring the other area. The result shows the mismatch of the maps created during drive in different directions. The scan-matching does not always remove such mismatch. However, the maximum positional inaccuracy was 35 cm with an average of 11 cm. The error can be further removed by implementing a loop closure technique, but the 11 cm result has already been well within the targeted resolution of 25 cm.



(a) One way SLAM

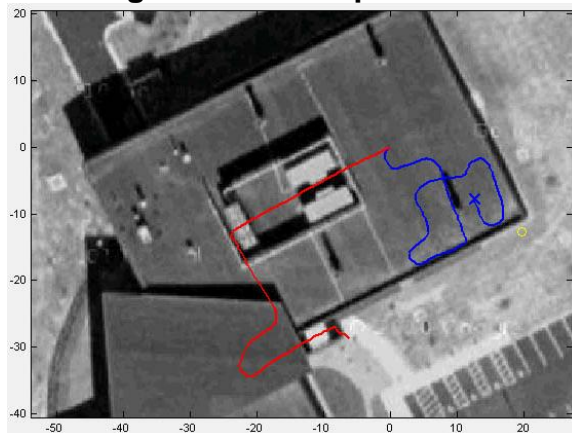


(b) Return SLAM

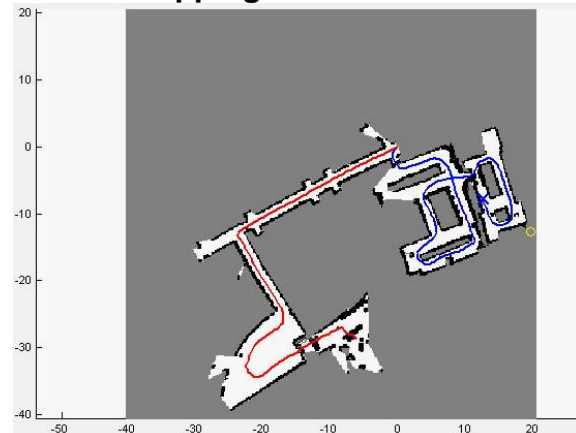
Figure 16 – Results of SLAM using the hybrid SLAM

Figure 17 shows the resulting UGV paths, OOI locations and global map in the two tests. Since the exploration was performed with an objective function with different parameters, the maps constructed are different. Nevertheless, the maps constructed commonly in the two cases show significant similarities, and this indicates the effectiveness of the developed multi-UGV system. One UGV traveled to the outdoor environment in Test 1. Further outdoor exploration failed due to disconnection to the wireless network, but the result shows the applicability of the developed system to the indoor-to-outdoor localization and mapping as well as the outdoor localization and mapping.

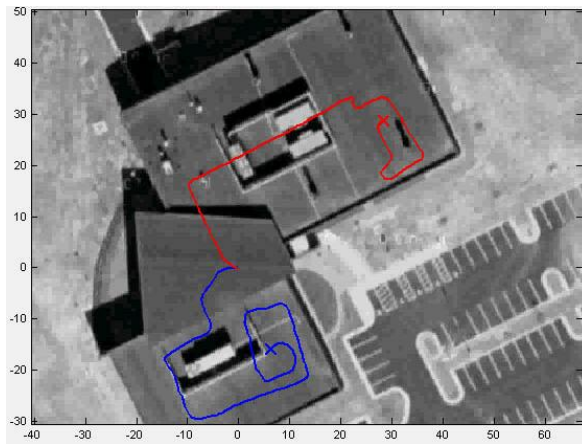
Figure 17 – UGV paths and localization and mapping results in Test 1



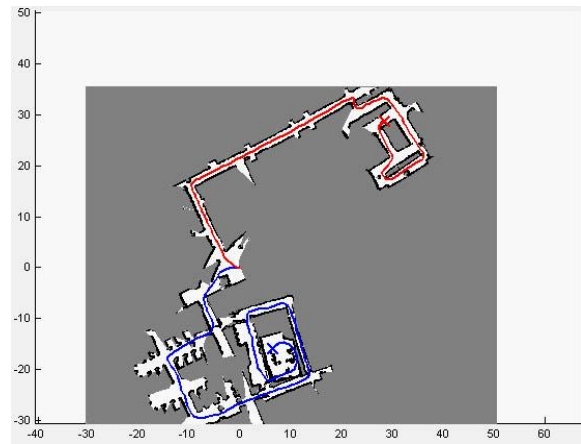
(a) UGV paths in Test 1



(b) Localization and mapping result in Test 1



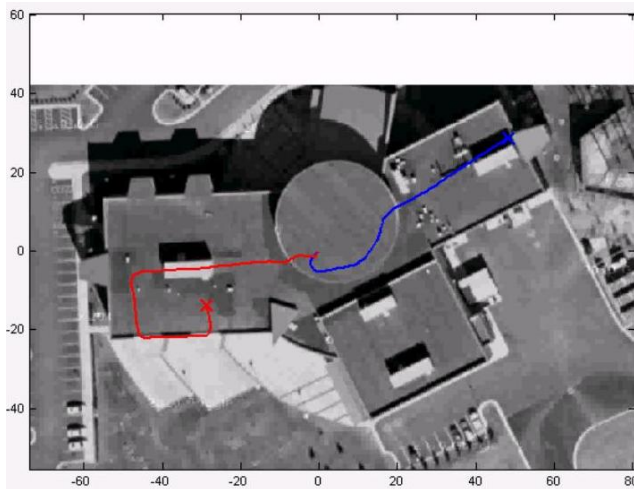
(a) UGV paths in Test 2



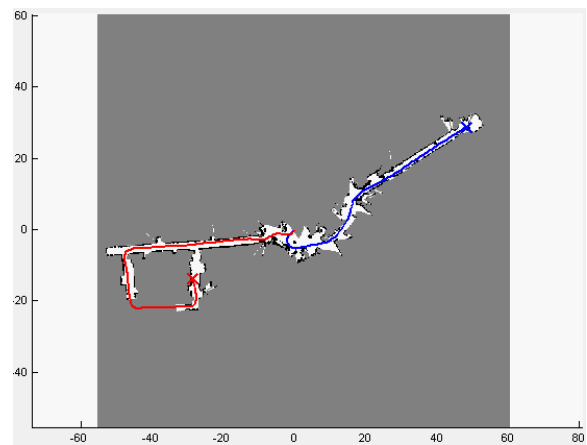
(b) Localization and mapping result in Test 2

Figure 17 – UGV paths and localization and mapping results in Test 2

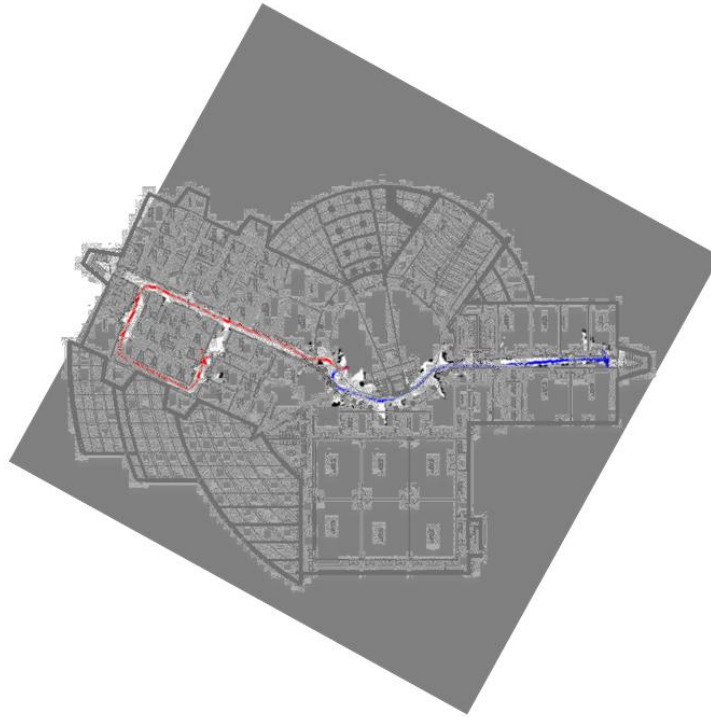
Figure 18 (a & b, below) shows the result of exploration in another building. This is a building with a conference hall and thus has a larger area as the dimensions indicate. The UGVs were manually driven to travel the areas which were not occupied by any functions. In order to investigate the accuracy of the constructed map, the map was overlapped on the floor plan as shown in Figure 18(c) on the next page. Although the UGVs were traveled at the average speed of 8 km/h, the map matched very well with the floor plan.



(a) UGV paths in a conference building



(b) Localization and mapping result in a conference building



(c) Constructed map shown on the floor plan

Figure 18 – UGV paths and localization and mapping results in a conference building

D – Conclusions

This final report has shown the final developed multiple UGVs and their autonomous navigation techniques developed by the US-Asian Team that can safely expedite reconnaissance in cluttered urban environments. Four high-performance UGVs with efficient and intelligent autonomous navigation capabilities have been developed. The use of long-range LIDARs enables the UGVs to perform cooperative exploration effectively. The hybrid feature-based/scan-matching allows OOI localization and map building within the targeted accuracy of 25 cm. The model-predictive control and the execution of the hybrid SLAM and the OGM on GPU make the autonomous navigation possible at a speed of at least 8 km/h. Performance tests in two buildings and one outdoor area have shown the efficacy of the developed multi-UGV system.